Plutonium production

In a nuclear reactor, only one of the neutrons from uranium fission is used to produce another fission. The other is absorbed, possibly by control rods (to prevent a growing chain reaction) or possibly by U-238. When U-238 absorbs a neutron, it becomes U-239. This is radioactive, and decays (it emits an electron and neutrino, and has a half-life of about 23 minutes) to an isotope of neptunium: Np-239. This isotope of neptunium is also radioactive. It emits an electron and a neutrino, with a half-life of 2.3 days, to turn into the very famous isotope of plutonium, the one that can be used for a nuclear weapons, Pu-239.

That is how we manufacture plutonium. We make it from U-238 by hitting it with neutrons in a nuclear reactor. The plutonium is a different chemical element from uranium, so when the fuel is removed, the plutonium can be chemically separated. That is not hard to do. The extraction of plutonium is called "uranium reprocessing." When we give nuclear power plants to underdeveloped countries, we do not allow them to do their own reprocessing, for fear that they would get a supply of plutonium in this way. Of course, we do give them nuclear fuel to run the reactors – but that is a mixture of U-235 and U-238, with too large of a fraction of U-238 for it to work as a bomb.

Breeder reactors

The Pu-239 is usually not considered nuclear waste, because it can be used itself to run a nuclear reactor. It is nuclear fuel. Moreover, if you put it in a nuclear reactor, you get three neutrons per fission instead of two. In a reactor, operating at constant (not exponentially growing) power, you want only one neutron per fission to produce another fission. What do you do with the extra two neutrons? Answer: put U-238 in the reactor, and make more plutonium.

Thus a reactor can make (out of U-238) more Pu-239 fuel than it consumes! Such a reactor is called a "breeder" reactor. It has the potential of turning all uranium, not just 0.7% of it, into nuclear fuel, and thereby increase the available fission fuel by a factor of 140.

There has been public opposition to breeder reactors. The two most common objections are:

1. "The plutonium economy." Breeder reactors would allow much greater use of nuclear power, but it means that plutonium would be widespread. Besides the fact that plutonium is radioactive, and therefor dangerous, some might be diverted by terrorists to make nuclear bombs. Proponents respond that the dangers of plutonium has been greatly exaggered, and that terrorists would not be able to make plutonium bombs because it is extremely difficult to get the required implosion to work adequately.
2. Reactor explosion. The most efficient kind of breeder reactor would use fast, not slow, neutrons. This is called a "fast breeder." But if fast neutrons are used, then the main safely aspect of the ordinary reactor is lost. In a fast breeder the chain

reaction could spread uncontrolled, and instead of just a meltdown, the reactor really could explode like an atomic bomb. Proponents respond that they would put in lots of other safely systems that would prevent this from happening.

Dangers of plutonium

Plutonium has been called "the most toxic material known to man." There is widespread fear of plutonium and of something referred to as a potential "plutonium economy". Because plutonium is so important in public discussion, it is worthwhile giving some of the physics facts.

The dangers of plutonium are analyzed in detail in a Lawrence Livermore National Laboratory Report that is available on the web at www.llnl.gov/csts/publications/sutcliffe/118825.html.

Here are the key facts: Plutonium is toxic both because of its chemical effects and because of its radioactivity. The chemical toxicity is similar to that of other "heavy metals" and is not the cause for the widespread fear. The dangers are different for ingestiion and for inhalation.

Ingestion of plutonium

For acute radiation poisoning, the lethal dose is estimated to be 500 milligrams (mg), i.e. about 1/2 gram. A common poison, cyanide, requires a dose 5 times smaller to cause death: 100 mg. Thus for ingestion, plutonium is very toxic, but five times less toxic than cyanide. There is also a risk of cancer from ingestion, with a lethal doze (1 cancer) for 480 mg.

Inhalation of plutonium dust

For inhalation, the plutonium can cause death within a month (from pulmonary fibrosis or pulmonary edema); that requires 20 mg inhaled. To cause cancer with high probability, the amount that must be inhaled is 0.08 mg = 80 micrograms. The lethal dose for botulism toxin is estimated to be about 0.070 micrograms = 70 nanograms. [1] Thus botulism toxin is over a thousand times more toxic. The statement that plutonium is the most dangerous material known to man is false. But it is very dangerous, at least in dust form.

How easy is it to breathe in 0.08 mg = 80 micrograms? To get to the critical part of the lungs, the particle must be no larger than about 3 microns. A particle of that size has a mass of about 0.140 micrograms. To get to a dose of 80 micrograms requires 80/0.14 = 560 particles. In contrast, the lethal dose for anthrax is estimated to be 10,000 particles

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[1] The toxicity of chemicals such as botulism toxin is not well known, since we don't do experiments on humans, and many people feel that experiments on animals is also improper. Some people estimate that the LD50 for botulism may be as low as 3 ng (rather than 70). An article by John S. Urbanetti M.D., FRCP, was once online at: http://www.janes.com/security/chemical_biological/news/cbw/cbw000627_1_n.shtml

of a similar size. Thus plutonium dust, if spread in the air, is more dangerous than anthrax – although the effects are not as immediate.

Depleted Uranium

When U-235 is enriched, there is some U-238 left over. This is called "depleted uranium." It is slightly less radioactive than ordinary uranium since the U-235 is gone. The remaining U-238 does decay by emitting an alpha particle, with a half life of 4.5 billon years, roughly the age of the Earth. That's why there is so much left on the Earth – only half of the orignal U-238 has decayed.

In contrast, U-235 has a half-life of 0.7 billion years. In the 4.5 billion year age of the Earth, it has gone through 4.5/0.7 = 6.5 half lives. That has reduced its abundance by a factor of $2^{6.5} = 90$. That's why there is so little left.

Depleted uranium is used by the military for certain kinds of weapons, particularly shells that are used to attack tanks and other armored vehicles. Depleted uranium is not used because of its radioactivity, but because of two other features it has: 1. It is very dense. With a density of 19 grams per cubic centimeter, it is almost twice as dense as lead. That is important for penetration. 2. When it hits a metal shield, it tends to form highly concentrated streams, instead of spreading out and splattering. This also helps it to penetrate armor.

People oppose the use of depleted uranium because it leaves radioactive material on the battlefield. Proponents say that the danger of radioactivity is small compared to the damage done by war, and that the alternative (lead) is also highly poisonous.

Fuel requirements

To get a gigawatt of electric power from a nuclear reactor, for a year, you must consume some uranium. The amount is surprisingly small: about 1 ton of U-235, which (if pure) takes a volume of about a cubic foot. This has to be extracted from ordinary uranium that would fill up a cube 2 meters on a side. If you are interested in how I got this number, you can read the optional calculation:

optional: uranium fuel calculation

We want to calculate the amount of U-235 needed to run a 1 gigawatt power plant for a year. We'll do a simplified calculation that will give us an approximate answer. As we said earlier, each fission of U-235 produces about 200 MeV of energy. Let's convert that to joules. 1 eV = 1.6×10^{-19} joules, so 200 MeV = $200 \times 10^{6} \times 1.6 \times 10^{-19} \approx 3 \times 10^{-11}$ joules.

How many do we need for a gigawatt-year of energy? A year is 3×10^7 seconds[2]. A gigawatt is 10^9 joules per second. So the number of joules in one year is $E = 10^9 \times 3 \times 10^7 = 3 \times 10^{16}$ joules.

So the number of fissions needed N is the energy needed divided by the energy per fission: $N = (3 \times 10^{16}$ joules$)/(3 \times 10^{-11}$ joules per fission$) = 10^{27}$ fissions. So we need 10^{27} atoms of U-235 to produce a gigawatt for a year.

We assumed that all of the energy goes into electric power. But that isn't true – only about a third does. So we really need 3×10^{27} U-235 atoms.

One mole contains 6×10^{23} atoms. So we need $(3 \times 10^{27})/(6 \times 10^{23}) = 5000$ moles. Each mole weighs 235 grams (since there are 235 protons and neutrons in each atom). So the weight of U-235 that we need is $5000 \times 235 \approx 10^6$ grams = 1 ton of U-235. Uranium has a density of 19 grams per cubic centimeter. So the amount of U-235 needed, 10^6 grams, is $10^6/19 \approx 50{,}000$ cubic centimeters, which is a cube with sides of 37 cm, a little more than a foot. So remember it this way: the amount of U-235 required is about a cubic foot.

This U-235 is found in natural uranium, but it is only 0.7%, i.e. it is 0.007 of the natural uranium. So the amount of natural uranium it takes to run a nuclear reactor for a year is about 1 ton/0.007 = 140 tons = 140×10^6 grams. With a density of 19 grams per cubic centimeter, this works out to (140 x106)/(19) = 7.4×10^6 cm^3, which is a cube with sides of about 2 meters.

Nuclear waste

The fission fragments from uranium all come from the uranium, so their weight is comparable. Thus, a year of operation of a nuclear power plant will produce about one ton of fission fragments. There may be a comparable amount of plutonium produced, but as discussed above, that is considered valuable fuel, and will be removed by chemical reprocessing. That's why the plutonium is not usually considered part of the waste. It is also much less radioactive than the fission fragments, since its halflife (24,000 years) is so long.

If they were concentrated, the fission fragments would take up a few cubic feet of volume. But it is expensive to do that, and so they are normally mixed in with larger amounts of unspent fuel, primarily U-238. This fuel with its fission fragments makes up the high level radioactive waste of nuclear energy.

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[2] That's the number you get if you take 60 seconds per minute, 60 minutes per hour, 24 hours per day, and 365 days per year: $60 \times 60 \times 24 \times 365 = 3.16 \times 10^7 \approx 3 \times 10^7$ seconds.